Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions

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Abstract: Thinning and prescribed fire are widely used to restore fire-suppressed forests, yet there are few studies of their effectiveness in Sierran mixed conifer. We compared stand conditions of replicated plots before and after a combination of thinning and burning treatments against an 1865 forest reconstruction. The historic forest had 67 stems/ha (trees $\geq$ 5 cm dbh), an equal percentage of shade tolerants and intolerants, stems randomly distributed at the stand scale, and a flat diameter distribution across size classes. The pretreatment forest averaged 469 stems/ha which were 84/14% shade tolerant/intolerant, highly clustered, and had a reverse J-shape diameter distribution. Thinning treatments failed to approximate historic composition, spatial pattern or diameter distribution. Treatments left too many small trees, removed too many intermediate-size trees (50-75 cm dbh), and retained a reverse J-shaped diameter distribution. Current old growth has fewer large trees than historic conditions, suggesting treatments should retain more intermediate-size trees to provide for future large tree recruitment. Understory thinning with prescribed fire significantly reduced stem density and produced a spatial pattern closest to historic conditions. Mixed-conifer restoration needs thinning prescriptions that vary by species and flexible rather than rigid upper diameter limits to retain some trees in all size classes.

Introduction

Sierran mixed-conifer forest, primary habitat for more vertebrate species than any other forest community in California (Mayer and Laudenslayer 1989), has been severely altered from a century of fire suppression. Historically these forests had a mean fire return interval of 12-17 years which has now shifted to more than 600 years by one estimate (McKelvey et al. 1996). Regional plans (SNFPA 2004) and national policies have general restoration guidelines typified by language in the Healthy Forests Restoration Act: "In carrying out a covered project, the Secretary shall fully maintain, or contribute toward the restoration of the structure and composition of old growth stands according to the pre-fire suppression old growth conditions"[1]. One measure of pre-fire suppression conditions for many western forests is to reconstruct stand conditions from the mid to late 19th century, a period which had an active fire regime (Fulé et al. 1997; Taylor 2004, Landis and Bailey 2005). Current efforts to mimic pre-fire suppression forest conditions in California's Sierra Nevada, however, are difficult to assess because most information on 19th century forest conditions is limited to narratives (Muir 1911; LeConte [1875] 1930), photographic comparisons (Gruell 2001) or early but limited forest surveys (Fitch 1900; Lieberg 1902; Moore 1913, Stephens and Elliot-Fisk 1998, Stephens 2000).

While many methods of Sierran forest restoration are possible, Stephenson (1999) suggested they can generally be grouped into two approaches: *structural* restoration which emphasizes first restoring historic stand structure and composition through mechanical thinning, and *functional* restoration which prioritizes restoring ecological processes such as fire. Some studies have suggested Sierran forests cannot be restored without first thinning the forest to reintroduce a clustered age cohort structure (Bonnicksen and Stone 1981; 1982). Others have suggested that prescribed fire can accomplish most stand reconstruction without first thinning the forest (Harvey et al. 1980; Stephenson et al. 1991). When thinning is used, treatments have been controversial because prescriptions often propose thinning some intermediate (> 50 cm diameter at breast height [dbh]) or large (> 75 cm dbh) trees both to restore stand structure and to provide enough revenue to pay for treatments. In spite of these controversies, there has been little research in the Sierra Nevada on the effects of burning and different thinning intensities on structure, composition and spatial pattern of forests, and how these compare to historic conditions (Fig. 1).

In 1997 we established and mapped permanent plots to be treated with a combination of burning and thinning treatments in 2000 and 2001. We were interested in how widely used restoration treatments affect forest structure, composition and pattern, and how treatments compare to a reconstruction of forest conditions which had an active fire regime. Specifically we had 3 objectives: 1) how do current forest conditions differ from stand structure, composition and pattern in 1865 (the year of the last widespread fire at our study site); 2) how do fire and thinning treatments affect diameter distribution, species composition and spatial structure of mixed conifer; and 3) which treatment is most effective at moving current stand conditions toward reconstructed forest conditions produced by an active fire regime. We examined forest conditions intensively at the Teakettle Experimental Forest where we were able to apply a controlled field experiment

[1] http://agriculture.senate.gov/forest/forhxadtsec.pdf

to replicated plots of old-growth, mixed-conifer forest, and sample ages and fire scars on stumps produced by the thinning treatments.

Methods

Study area

The study took place within the Teakettle Experimental Forest, a 1300 ha reserve of old growth on the north fork of the Kings River within the Sierra National Forest (Fig. 2). The elevation ranges from 1900-2600 m, and annual precipitation of approximately 125 cm falls almost entirely as snow between November and April (North et al. 2002). Teakettle's most common soil is mapped as a well-drained, mixed, frigid Dystric Xeropsamment, formed from decomposed granite, typical of many southern Sierra forests (Anonymous 1993).

Within Teakettle, forest type varies by elevation, grading from mixed conifer at lower elevations to red fir (*Abies magnifica*) on mid-slope, and to red fir and lodgepole pine (*Pinus contorta*) at higher elevations. Approximately 65% of Teakettle's forest is mixed conifer, which characteristically contains white fir (*Abies concolor*), red fir, California black oak (*Quercus kelloggii*), sugar pine (*Pinus lambertiana*), incense-cedar (*Calocedrus decurrens*), and Jeffrey pine (*Pinus jeffreyi*) (Rundel et al. 1988). As in most of California's mixed-conifer forests, white fir dominates stem density and basal area at Teakettle; however, sugar pine and Jeffrey pine are the largest diameter and tallest trees (North et al. 2002). An analysis of fire scars in Teakettle indicated that prior to European settlement, the fire return interval for the 200 ha experimental area was 11-18 years, and the last widespread fire (> 3 ha) occurred in 1865 (Fiegener 2002, North et al. 2005a).

Our research focused on a 200 ha contiguous block of mixed conifer with similar soils (all mapped as the Cagwin series [Anonymous 1993]) derived from decomposed granite typical of the western slope of the Sierra Nevada. In this area, 18 permanent four-ha plots were established (Fig. 2) from prior data (North et al. 2002). Plot size (4 ha) was established using variogram analysis to estimate an area sufficiently large enough to include the range of variable forest conditions found in mixed conifer. Stand structure and the understory community were sampled on 600 quadrats on a 50 by 50 m systematic grid across the 200 ha block and quadrats were grouped with cluster analysis. The 4 ha plots were located within the 200 ha block so that each plot included the same proportional representation of the 4 vegetation conditions (closed canopy, shrub, gap and rock/shallow soil patches [North et al. 2002]) identified in the cluster analysis of the quadrats. An analysis of the forest structure and composition found no significant pretreatment differences between the 18 plots (North et al. 2002).

Treatments

The 18 plots were assigned to one of six treatments determined by the experimental design, a full factorial, crossing two levels of burning treatments (prescribed fire and no burn) and three levels of thinning treatments (none, understory and overstory) (Fig. 2). For some plots, management and operational constraints (e.g., presence of a sensitive species such as the pine marten) limited which treatments could be applied, but after applying these constraints, treatments were allocated as randomly as possible. The understory prescription followed guidelines in the California spotted owl

(CASPO) report (Verner et al. 1992), which removes all trees between 25 and 76 cm (10 and 30”) dbh while retaining at least 40% canopy cover. Although designed initially for minimizing impact to spotted owl habitat, the CASPO guidelines became the standard forest practice in the 1990s and are still widely used as a fuel reduction treatment (SNFPA 2004). The overstory prescription removed all trees > 25 cm dbh except for 22 large diameter trees per hectare, which were left at regular spacing (approximately 20 m apart). The overstory thinning was widely practiced in Sierran forests before CASPO, and at Teakettle its marking resulted in a prescription of cutting dominant overstory trees up to 100 cm (40”) dbh. Increasing the diameter limit from 30 to 40” was widely debated in the late 1990s as a means of increasing sale revenues so that more stands could be treated for fuel reduction. The thinnings were applied in fall of 2000 (thin and burn plots) and early spring of 2001 (thin-only plots). Trees were limbed and topped where they fell and merchantable logs removed. The prescribed fire was applied by the Sierra National Forest following their standard operating procedures. Fuels from the thinning operations were left to dry for one year, and the prescribed fires were lit in fall of 2001 a week after the first substantial (2 cm) rainfall. All plots were burned within a one week period and the fire was extinguished by snow a week later.

Data collection and stand reconstruction

Using a surveyor’s total station, all trees and snags (≥ 5 cm dbh; N = 35,418) in the eighteen 4 ha plots were measured, identified to species, mapped, and permanently tagged during the 1998-2000 field seasons before treatments were applied. Snags were assigned a decay class (Cline et al. 1980) and a visual estimate of height recorded. Following treatments all plots were re-sampled and mapped during the 2002-2004 field seasons using the same protocols. All logs (≥ 30 cm diameter) were tagged, mapped (four corners) and assigned a decay class (Maser and Trappe 1984). Only logs in decay classes I-IV were inventoried because field technicians could not reliably identify the dimensions of decay class 5 logs. Following treatments, logs were inventoried and mapped again, this time using diameter and azimuth, and identified to species.

To assess canopy cover, 402 hemispherical photographs were taken from regularly spaced sample points in each plot before and after treatments with a Nikon Cool Pix 950 digital camera and a Nikkor hemispherical FC-E8 0.21X fisheye converter (180° angle) lens. All photographs were taken in black and white at dawn or dusk with uniformly cloudless conditions using a level tripod, with the top of the photo oriented to true North.

To reconstruct historic stand structure to 1865 conditions, we generally followed methods used in Southwest ponderosa forests (Fulé et al. 1997, Mast et al. 1999, Moore et al. 2004) in which the size, species composition, and location of live trees during an active fire period are estimated from current live trees, snags and logs. We modified these reconstruction methods because of the mix of shade-tolerant and –intolerant species in mixed conifer, and added a measure of current growing space to refine species-specific estimates of past diameter.

First we took 539 ground-level cross section ‘cookies’ from post-treatment stumps in direct proportion to the species composition (by frequency) of stems within the stand. This provided a much higher sample size for the three shade-tolerant species, white fir, red fir, and incense-cedar, which should have greater variability in annual basal area increment than the shade-intolerant pines (Oliver and Larson 1996). The 539 sample cookies were cut into cross sections and sanded with up to 400 grit sandpaper to improve visual identification of tree ring boundaries. Tree rings were measured from the last year of growth to the pith using a microscope and a Velmex "TA" tree ring system (Velmex Inc., Bloomfield, NY). Measurement resolution was 0.001 mm. Series were manually cross-dated using standard procedures (Stokes and Smiley 1968), and the annual basal area increment (BAI) for each tree was calculated for each year from 1865 to 2000. We subtracted the 1865 to 2000 radial increment to estimate ground-level inside bark diameter of each stem in 1865. Next, we used species-specific equations to estimate 1865 outside bark diameter at breast height for each tree (Dolph 1981).

We calculated an approximation of local competition for each of the cookie-sampled trees using Thiessen polygons. The size and distribution of Theissen polygons has been used to evaluate the impact of density, growing space and competition of neighboring plants on plant succession (Mithen et al. 1984, Kenkel et al. 1989). Using the stem map and ARC/INFO software, the area around each tree was bisected by a line equidistant between adjacent stem locations, and the lines are connected to form a polygon around each cookie-sampled tree location. The polygon's area is an approximation of the potential growing space, in square meters, for an individual tree. Polygon size is a function of local stand density, with smaller areas indicative of dense, 'dog hair' conditions. Polygons were then weighted by dividing each polygon's area by the basal area of the sample tree to take into account the greater growing space demands (i.e., light, water and nutrients) of larger trees. This approximation of growing space is estimated from current conditions and therefore its utility is based on an assumption that reductions in BAI from fire-suppressed stem density increases will be correlated with present stand conditions.

For each species we built regression models to predict 1865 dbh from dbh in 2000 (recorded before the tree was cut) and the weighted Theissen polygon size. Using the best-fit equations for each species, we than estimated 1865 diameters for all trees in the eighteen plots using the 72 ha pre-treatment stem map and the weighted Theissen polygon calculated for each tree.

In addition to the live-tree estimate, reconstruction estimates were made using the stem map of snags and logs. In mixed conifer, the year of death often cannot be determined using increment cores because many pieces have extensive heartwood and sapwood rot. To estimate when a snag died, we used the field rating of the decay class of each snag and applied published estimates for the transition time between decay classes for Sierran mixed-conifer species (Raphael and Morrison 1987; Morrison and Raphael 1993) to estimate the decade in which a snag originated. Using the 539 cookies, we calculated mean BAI for each of the 5 principle species in 25 cm diameter classes. We estimated each snag's live 1865 dbh using the formula:

1865 dbh = 2000 dbh - [(midyear of death decade – 1865) * (BAI)] + estimated bark thickness (if missing in 2000)

To estimate 1865 tree size from current logs, we used published estimates of log age for different decay classes (Kimmey 1955; Harmon et al. 1987) to estimate the decade during which a log originated. We then used time estimates for snag fall rates in unburned forest (Raphael and Morrison 1987) to estimate decade of tree death and then applied the equation listed above to estimate dbh in 1865. This approach should be a conservative estimate of tree size because live trees may be wind toppled and directly become logs without going through a snag phase. Field observations, the rarity of tip-up mounds, and the lack of a consistent azimuth in log orientations (Innes et al. in press), however, suggest most trees at Teakettle go through a snag phase rather than directly becoming logs due to wind events.

While there are several limitations to these reconstruction methods, the most significant is our estimate of the density and location of small trees. Our tally of logs and snags in 1998-2000 would fail to detect small diameter trees which died after 1865 and completely decayed before our survey. Using estimates of log decay rates (Harmon et al.1987) and snag fall rates (Morrison and Raphael 1993), we can roughly estimate that small diameter ($\leq$ 25 cm diameter) white fir, the species with the fastest decomposition rate, that died in 1940 or later would still have at least 20% of their bole mass in 2000 and be detected in our log survey (decay classes 1-4). We have no way of estimating how many small trees died before 1940 or how many are still alive. An earlier demography study at Teakettle did find many small-diameter white firs from the 1880s still alive even in high-density thickets (North et al. 2005a). Our survey is much more likely to detect larger diameter trees and other species which have slower decay rates. This bias means our 1865 reconstruction underestimates small tree density and small scale clustering (because small stems are usually clumped). This bias is less likely to significantly affect our estimates of basal area, volume, density of large trees or large scale spatial patterns.

Analyses

To develop species-specific models for estimating 1865 diameter from 2000 dbh we assessed whether BAI and weighted Thiessen polygon values were normally distributed using the Shapiro-Wilks test. Values for the three shade-tolerant species (white and red fir, and incense-cedar) and all weighted Thiessen polygons values were not normally distributed and therefore were log transformed.

To evaluate different predictive models using combinations of BAI, weighted Thiessen polygon size, and interaction terms, we used Akaike's Information Criteria (AIC) (Burnham and Anderson 2002). All terms were added to the model, and then terms were dropped if their C_p statistic (the likelihood version of AIC in S-PLUS) was lower than the C_p statistic for the full model.

Current canopy cover was estimated using hemispherical photographs analyzed with Gap Light Analyzer 2.0 (Frazer et al. 2000). We compared measures of stand structure (basal area, density, quadratic mean diameter, volume and species composition percentages) between all treatments and the 1865 reconstruction using ANOVA and a Tukey's post-hoc test. All analyses were completed using S-Plus statistical software (S-Plus 2001).

Tests of spatial distribution were made using Spatial Point Pattern Analysis software (Haase 1995) and univariate Ripley's K analyses. Ripley's K compares distances between all location points in the same plane (Ripley 1979; Diggle 1983) using the reduced second moment measure or K function to examine spatial associations. We calculated 99% confidence intervals using 100 Monte Carlo simulations. We examined the distribution of all trees in the 18 plots in estimated 1865 conditions, and before and after treatments.

Results

The most parsimonious models for estimating 1865 dbh for all species except Jeffrey pine included two terms, 2000 dbh and weighted Thiessen polygon size. Multiple adjusted R^2 values were 0.69 for white fir, 0.70 for red fir, 0.63 for incense-cedar and 0.73 for sugar pine. The best model for Jeffrey pine used only 2000 dbh and had an adjusted R^2 of 0.83.

Pre-treatment forest conditions at Teakettle significantly differed from the active fire forest reconstruction in stem density, quadratic mean diameter, and species composition (Table 1). Although the 1865 forest had a much lower stem density than modern conditions (67 vs. 469 trees/ha), there was no significant difference between the two conditions in basal area (51.5 vs. 56.4 m^2/ha) or volume (393.2 vs. 434.6 m^3/ha), because the fewer trees were larger in size (49.5 vs. 19.6 cm). A significant shift in forest composition has occurred with pretreatment conditions having 84% and 14% shade tolerants and intolerants, compared to 51% and 49%, respectively, in 1865. Most of that change was due to the significant increase in the percentage of white fir and decrease in Jeffrey and sugar pine percentages.

All of the thinning treatments significantly reduced basal area below current and historic conditions, however all except the overstory thin and burn (93.6 stems/ha) still retained significantly more stems than were present in 1865 (Table 1). Canopy cover was reduced directly in proportion to thinning intensity with no significant differences between burn and no burn plots within the same thinning intensity. None of the treatments produced a significantly different quadratic mean diameter from one another (21.9-28.9 cm); however, all were significantly lower than historic conditions (49.5 cm). All treatments reduced stem volume, but only the two overstory thinning treatments (200.5 and 141.8 m^3/ha) significantly reduced volume below historic (393.2 m^3/ha) or current conditions (434.6 m^3/ha).

Stand composition was only marginally affected by treatment and still significantly differed from historic conditions. None of the treatments significantly reduced the percent of white fir (57.7-67.6%) which was almost double the historic value (33.7%). Both burning and thinning treatments (20.8 and 22.4%) significantly increased the percentage of incense-cedar compared to other treatments (9.5-15.8%), current (13.4%) and historic (14.5%) conditions. There was no significant difference in either sugar and Jeffrey pine percentages between treatments, but all treatments had about 1/3 the pine percentage of historic conditions. Burning increased small stem mortality and produced significantly higher snag densities (92.4-123.4 stems/ha), but did not impact species composition, basal area or canopy cover substantially.

The most significant difference in diameter distribution was between historic conditions and the current forest pre- and post-treatment (Fig. 3). In 1865, the diameter distribution was almost flat with nearly equal stem numbers in each 25 cm dbh class. In contrast, all of the treatments have very high stem numbers in the small diameter classes and much fewer large size trees. All treatments do not significantly change the reverse-J shaped distribution present in the pretreatment forest. The number of 50-75 cm stems was reduced in all thinning treatments (4.2-8.9 stems/ha) below historic levels (11.2 stems/ha). In size classes greater than 75 cm, overstory thinning significantly reduced the number of large trees below their historic density. Historically there were more trees in the large size classes (>100 cm dbh) than in current conditions or following any of the treatments, particularly for the largest size class (>150 cm dbh).

Tree spatial patterns have significantly changed from 1865 to current conditions with the most noticeable change being the sparse, low-density distribution in 1865 (Fig. 4a) compared to pretreatment conditions (Fig. 4b). The reconstruction shows trees were slightly clustered up to 60 m (Fig. 4a) compared with pretreatment stem distribution where trees were strongly clustered. At this scale, the clustering effect is strongly influenced by the high number of small trees regenerating in existing tree groups (North et al. 2004). Burn treatments (Fig. 4c, 4e, and 4g) killed more small trees but there was only a small reduction in how strongly trees were clustered at small to intermediate distances (0-60 m) over similar treatments without burning. Thinning-only treatments (Fig. 4d and 4f), which did not remove trees under 25 cm dbh, did little to reduce clustering over the 0 to 60 m scale.

At larger scales (> 60 m) the reconstruction shows that the 1865 stem distribution was random (Fig. 4a). Only the burn and understory thinning treatment (Fig. 4e) produced a similar distribution at this scale. Burning alone (Fig. 4c) slightly reduces the degree of clustering at large scales from pre-treatment condition. The understory thinning (Fig. 4d) reduces clustering at intermediate scales (40-60 m) but did not restore a random distribution at larger scales. As expected the overstory thin and burn treatment (Fig. 4g), which left 22 large trees per hectare evenly spaced, significantly made stands regularly distributed at large scales. The pattern, however, was not present in the overstory thin-only treatment (Fig. 4f) because many small trees (<25 cm dbh) were left producing a clustered distribution at larger scales.

Discussion

We compared an 1865 reconstruction to current and treated stands to assess whether treatments approximate forest conditions produced by an active fire regime. This comparison, however, is not an endorsement of regressing forests to a pre-European condition. Efforts to recapture a historic condition are probably misguided as elimination of Native American ignitions (Anderson and Moratto 1996), changes in grazing intensity (Douglass and Bilbao 1975; Rowley 1985), and climate change (Millar and Wolfenden 1999; Pierce et al. 2004) have substantially changed factors that influenced forest composition and structure. A goal of effective restoration is re-establishing conditions characteristic of the evolutionary environment of an ecosystem (Falk 1990; Society for Ecological Restoration 1993). Many studies have shown that frequent, low-intensity fire has been a key process shaping Sierran mixed conifer (Agee et al. 1978; Vankat and Major 1978; Kilgore and Taylor 1979; Parson and DeBenedetti 1979). Our comparison with 1865 conditions is intended as a reference point for mixed-conifer conditions produced by an active fire regime and not as a strict prescription for contemporary restoration (Falk 1990; White and Walker 1997).

Our analysis supports the concept that active fire regime stands were low-density, with a high proportion of large size trees, and a substantially higher proportion of shade-intolerant pine species. Lieberg (1902) describes central Sierra mixed-conifer forests in which densities were low and most were stems > 62 cm (25”) dbh. Sudworth (1900a; 1900b) using data from a limited number of mixed-conifer plots shows a higher average density (92 stems/ha) than we found (Table 1), but a much higher number of very large trees. A large scale (>2300 plots) 1930's survey of Sierran forests (Bouldin 1999) found much higher mixed-conifer stem densities (140-218 stems/ha) than we did, but this was already several decades after Sierran fire regimes had changed. Estimates of species composition vary by location (McKelvey and Johnson 1992) with shade-intolerant pine making up 30-50% of the stems (Moore 1913; Sudworth 1900a; 1900b; Fitch 1900) in early surveys. These historical data sets, however, should be treated with caution because there is little information on sampling protocols or how plots were located. Bouldin (1999), for example, has suggested that Sudworth's data is significantly biased from locating plots in exemplary groves of large trees.

Our estimate of 1865 forest conditions should be viewed with caution because it is limited by problems common to reconstruction analyses and the constraints of our field sampling. White and Walker (1997) suggest that all reconstructions be explicit about their spatial and temporal limits, and potential biases in their reconstruction methods. Our analysis is focused on one old-growth area where we have the intensive data needed to reconstruct stand conditions on 72 ha back to the last fire. Any effort to reconstruct earlier conditions would be difficult because frequent fires would have consumed woody material. Our reconstruction methods are also limited by imperfect predictive models of past diameter, broad estimates of death date from decay class, and better records for species, such as incense-cedar, with slower decay rates. Our estimates of the density and spatial location of small trees are less accurate than our large tree estimates because our 1998-2000 survey would miss small trees that died within a few decades of Teakettle's last fire in 1865. Our estimates of 1865 stand conditions, however, are similar to a reconstruction of 19th century stands in the Lake Tahoe area, which found comparable stem densities and stands dominated by large pines (Taylor 2004). We know of one contemporary mixed-conifer area, Aspen Valley in Yosemite National Park, with a fairly active fire regime (3 understory burns in the last 40 years) that has never been mechanically thinned. Aspen Valley has a higher density than Teakettle's reconstruction (102 vs. 69 stems/ha), and a higher percentage of pine (64%), but a similar low density of small size trees and a nearly flat diameter distribution curve (Monica Buehler, Yosemite N.P. Fire Ecologist, unpublished data). We believe Teakettle's 1865 forest conditions are within the range of historical forest surveys and other reconstructions. Our focus with this research was to compare stand conditions produced by different restoration treatments with those produced by an active fire regime in old-growth mixed conifer.

Our reconstruction suggests that effective treatments should drastically reduce small tree (< 50 cm dbh) densities, retain some intermediate and all large trees, significantly decrease the percentage of white fir and reduce stem clustering. None of the treatments in our experiment achieved all of these objectives, but the understory thinning and prescribed burn was more effective than the other treatments.

All treatments had about 10 times more 5-25 cm dbh trees than our rough estimate of this size class in 1865. Our methods underestimate small tree density but even with a tripling of our estimate, treatments would still have more than 3 times too many small trees. Mechanical thinning prescriptions did not cut any tree less than 25 cm dbh (10") based on the assumption that logging damage and prescribed fire would substantially thin this size class (Mark Smith, Sierra National Forest, personal communication). Logging damage and prescribed fire did reduce the number of stems by 15-65% in the 5-25 cm size class, but even the most intense treatment, overstory thinning and prescribed fire still averaged 87 small stems/ha compared to roughly 9 stems/ha in 1865. These small trees are usually unmerchantable, so their reduction in restoration treatments often depends on whether funds are available for a prescribed burn or for their removal with a supplemental service contract. Repeated prescribed burns would also help reduce this size class toward historic conditions.

All thinning and thinning/burning treatments reduced trees to near historic levels in the 25-50 cm class, but removed too many trees in the 50-75 cm class (Fig. 3). In the Sierra Nevada some of the controversy over restoration treatments has focused on the 50-75 cm size class because the trees have enough commercial value to help pay for thinning and prescribed fire treatments, but they also provide the next generation of large, old trees. At Teakettle, the reconstruction suggests this size class had approximately 11 trees/ha while thinning treatments significantly reduced this size class's density (4-9 trees/ha) below historic levels (Fig. 3). Trees remain in this size class even in the understory prescription (removal of all trees between 25 and 75 cm) because of errors in marking, wildlife 'leave trees' and leaving trees that are hazardous to fall.

Current Sierran thinning prescriptions (i.e., the understory treatment), leave all trees $\geq$ 76 cm (30") which in our experiment left comparable stem densities in the 75-99 cm class to 1865 conditions. Overstory thinning (removing trees up to 100 cm or 40" dbh) significantly reduced the density of large trees ($\geq$ 76 cm dbh) below 1865 levels and drastically reduced stand basal area and volume, producing a stand structure that substantially departed from historic conditions. For trees $\geq$ 100 cm, 1865 had a higher density than any of the treatments or even current unharvested, old-growth conditions. Smith et al. (2005) suggested this reduction in large trees in current old growth may be due to recent mortality from pest and pathogens during extended droughts. Some studies (Ferrell et al. 1994; Ferrell 1996) suggest that modern increases in stem density increase moisture stress, such that during droughts tree vigor declines and mortality increases from pests and pathogens. This implies that even in stands of unmanaged old growth, current large tree density may be lower than was present under an active fire regime.

Restoration thinning prescriptions sometimes rely on principles of uneven-aged silviculture (Smith 1986), which suggest thinning to a negative exponential or reverse-J shaped diameter distribution for diversifying structure. O'Hara (2001; O'Hara and Geof 2004), however, has pointed out seral development and local disturbance patterns can produce a wide variety of diameter distributions in natural stands. Although the current diameter distribution at Teakettle and in other old-growth stands (Ansley and Battles 1998; Minnich et al. 1995) has a reverse-J shape, Bouldin (1999) found a wide variety of diameter distributions in stands in the 1930s. The 1865 reconstruction suggests that under an active fire regime, Teakettle may have had a much flatter diameter distribution. Our reconstruction methods underestimate small tree densities and lower the left side of the diameter distribution below what it likely was in 1865. We believe, however, it's unlikely that we've underestimated this size class's density by ten fold, the increase needed to produce a reverse-J distribution. An earlier study of Teakettle's tree demography found frequent episodes of mortality and establishment following fires and wet climate years (North et al. 2005a). This demographic pattern could produce a fairly flat diameter distribution if diameter was loosely correlated with age in low density open stands produced by frequent fire.

Species composition has substantially shifted from almost a 50/50 split between shade-tolerant (fir and cedar) and intolerant (pine) species in 1865 to 84% and 14%, respectively, in 2000 in Teakettle's untreated forest. Treatments did not fundamentally change this composition. The composition of the thinned trees was similar to current stand composition because the thinning prescription was strictly based on diameter. White fir, which is considered fire sensitive, should suffer higher mortality than pine in a prescribed burn. However, in our study and in others (Hanson and North 2006), many white fir were large enough to be fire resistant to all but the hottest spot burns. Similar to Van Mantgem et al. (2004), we had many large sugar pines die even under moderate burn conditions. These patterns suggest more field manipulation studies are needed to assess optimal fire frequency and intensity for increasing pine percentage in treated forest stands.

The prescribed fire without thinning treatment had only a moderate effect on stand conditions in our experiment probably because it was a low-intensity late fall burn. As is typical in the Sierra Nevada, Teakettle's prescribed fire was lit 'off-season' in late October for easier containment and when air quality conditions allow more burning. Fire may not do as much 'work' in this condition of lower temperatures and higher humidity without the addition of thinning slash to fuel fire intensity and increase burn coverage. Prescribed fire may need to be repeatedly applied to help move stand structure toward historic conditions. Stem density was significantly lower and snag density higher in both thinning and burn treatments where the fire burned hotter than in the other treatments. In these late fall burns, the importance of thinning before prescribed burning may be that it increases the extent and intensity of the fire.

Small-scale stem patterns appear to have always been clumped but current and treated forests are significantly more clustered than in 1865. Limitations in our reconstruction methods will produce underestimates of small scale clumping; however we believe this bias is unlikely to make up the pronounced difference between historic and modern conditions. Reducing small scale density can be an important measure of restoration because it contributes to fuel loading (Stephens and Moghaddas 2005), moisture stress (Feeney et al. 1998), and low light understory conditions that reduce plant diversity (North et al. 2005b) and shade-intolerant regeneration (Gray et al. 2005). Thinning treatments in our experiment did little to reduce this clustering because there was limited incidental mortality in the 5-25 cm size class produced by mechanical removal of larger trees. Prescribed fire did reduce small scale clustering particularly with higher burn intensities in the thinned plots, but many small trees still survived. Effective restoration may require more aggressive removal of stems in this size class, reducing density toward the 10 stems/ha suggested in the reconstruction.

Our study also suggests that restoration treatments need to reduce larger scale (>60 cm) clustering and produce a more random distribution of stems at the stand level. Comparing historic and current conditions in three forest communities (Jeffrey pine-white fir, red fir-western white pine, and lodgepole pine) in the Lake Tahoe Basin, Taylor (2004) also recommended that restoration treatments should reduce clustering and produce a more random distribution. Teakettle's pretreated forest was strongly clustered and most treatments failed to achieve a random distribution at large scales. Understory thinning and burning was the most effective at approximating historic spatial structure because it retained all large trees, reduced stem density, and provided slash which increased fire intensity and mortality of small trees.

In our experiment one of the main reasons treatments did not restore active-fire stand conditions was because prescriptions thinned stands based on a strict diameter limit applied to all species. Many Sierran mixed-conifer stands have a small percentage of old shade-intolerants and in these cases few if any ponderosa, Jeffrey and sugar pine need to be thinned. Strict diameter limits also left too many small trees and over harvested intermediate-sized trees reducing future replacements for dying large trees. At Teakettle, 2-5 large trees/ha (> 75 cm dbh) died following understory thinning and prescribed burning treatments. This loss combined with the current deficit of large trees (> 150 cm) suggests that more intermediate size trees may need to be retained to provide for large tree development. Understory thinning combined with prescribed fire was most effective at moving stand conditions toward those produced by an active fire regime, but new thinning prescriptions may be needed that vary by species and that retain more intermediate-sized trees to provide for future large tree recruitment.

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Table 1. Stand structure and composition in 1865 (reconstructed), pretreatment, and for 5 treatments at the Teakettle Experimental Forest. Species composition percentages were calculated using stem frequency. Other species and snags could not be estimated for the 1865 reconstruction. Canopy cover was calculated from 67 hemispherical photographs taken in each treatment. Values within the same row with different superscripts are significantly different (p< 0.05, Tukey's post-hoc ANOVA analysis). Species composition percentages for the 1865 reconstruction were calculated using all trees but only those logs and snags which could be identified to species.

Stand attribute	1865	Pretreatment	Understory thin only	Overstory thin only	Burn only	Burn/Under -story thin	Burn/Over-story thin
Basal area (m^2/ha)	51.5[a]	56.4[a]	41.2[b]	22.7[c]	53.7[a]	37.5[b]	17.2[c]
Total Density (stems/ha)	67[a]	469[b]	239.5[c]	150.3[d]	353.8[e]	143.4[d]	93.6[a]
Cut (stems/ha)	NA	0	170.8	192.3	0	162.8	198.9
B.A. removed (m^2/ha)	NA	0	20.2	33.9	0	21.3	37.0
Canopy cover (%)	Unk	80.7[a]	72.8[b]	63.4[c]	80.5[a]	70.9[b]	60.2[c]
Quadratic mean dbh (cm)	49.5[a]	19.6[b]	23.4[b]	21.9[b]	22.0[b]	28.9[b]	24.2[b]
Volume (m^3/ha)	393.2[a]	434.6[a]	397.7[a]	200.5[b]	423.0[a]	372[a]	141.8[c]
Shade tolerant:							
Abies concolor	33.7%[a]	67.6%[b]	67.2%[b]	66.3%[b]	67.6%[b]	64.1%[b]	57.7%[b]
A. magnifica	2.9%[a]	3.0%[a]	4.7%[a]	1.9%[a]	2.5%[a]	1.2%[a]	1.0%[a]
Calocedrus decurrens	14.5%[a]	13.4%[a]	11.8%[a]	9.5%[a]	15.8%[a]	20.8%[b]	22.4%[b]
Shade intolerant:							
Pinus Jeffreyi	22.1%[a]	6.2%[b]	3.9%[b]	8.1%[b]	3.6%[b]	7.4%[b]	7.6%[b]
Pinus lambertiana	26.8%[a]	7.9%[b]	9.8%[b]	12.1%[b]	9.2%[b]	5.1%[b]	8.8%[b]
Other*	Unk.	1.9%[a]	2.6%[a]	2.1%[a]	1.3%[a]	1.4%[a]	2.5%[a]
Snag (stems/ha)	Unk.	39.0[a]	37.8[a]	32.3[a]	92.4[b]	120.3[b]	123.4[b]

* Other species were the following hardwoods: California black oak (*Quercus kellogii*), interior live oak (*Q. wislizenii*), canyon live oak (*Q. chrysolepis*), bittercherry (*Prunus emarginata*), and willow (*Salix spp.*).

Figure captions

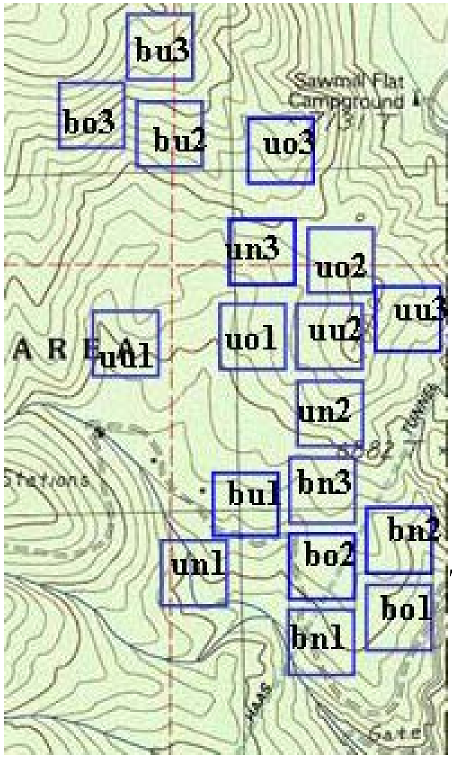
Fig. 1: Forest conditions in mixed conifer in a) 1900 (Tuolumne county), b) Teakettle pre-treatment (2000), and c) Teakettle after an understory thin and burn treatment (2003).

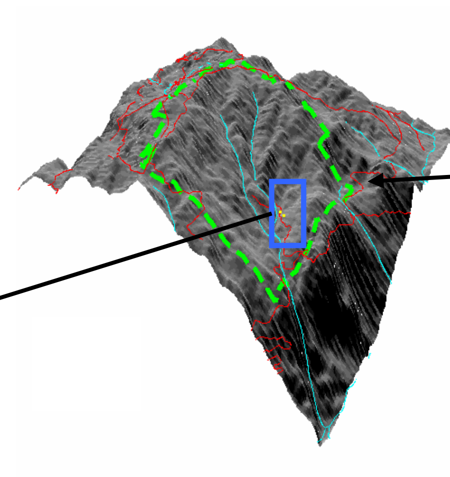
Fig. 2: Location and shape (30 m. digital elevation model) of the Teakettle Experimental Forest. The table shows the treatments in the full-factorial design and the topographic map indicates each 4 ha plot location, treatment (from the table's abbreviations) and replicate number (1-3).

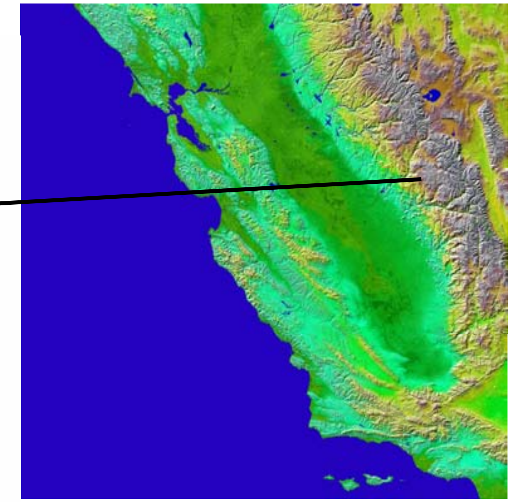
Fig. 3: Density of live trees (stems per hectare) in 7 size classes for 7 conditions in the Teakettle Experiment. Note that the smallest size class is less than a 25 cm range because only trees $\geq$ 5 cm were tallied.

Fig. 4: Stem distribution and spatial analysis of all live trees ($\geq$ 5 cm dbh) for a representative plot in each of 7 conditions. Conditions are; a) 1865 reconstruction, b) pretreatment, c) burn only, d) understory thin only, e) burn and understory thin, f) overstory thin, and g) burn and overstory thin. Circle size on the stem map is proportional to diameter and species are color coded where abco is white fir, abma is red fir, cade is incense-cedar, pije is Jeffrey pine, pila is sugar pine and unk is unknown. The graph for each condition shows the spatial distribution calculated using univariate Ripley's K. The stem pattern is the solid line and 99% confidence intervals are the two dashed lines. The stem pattern is considered to be significantly aggregated for those distances (m along the x axis) over which the solid line is above the upper dashed line, and regularly distributed for those distances over which the solid line is below the lower dashed line. Stem map and Ripley's K analysis for figures 4a, 4b, and 4e are for the same 4 ha plot (BU1) in years 1865, 2000, and 2003 respectively.

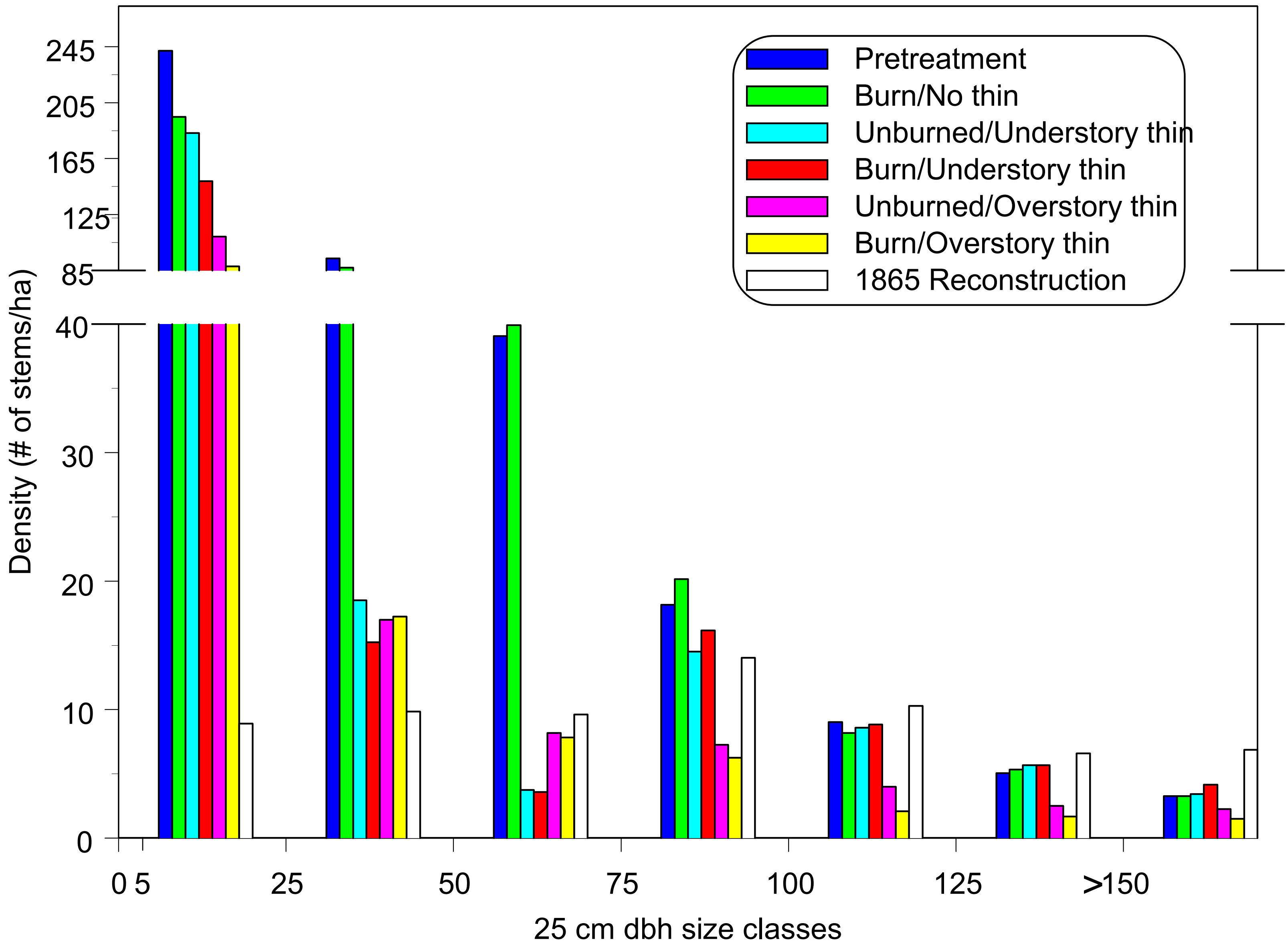

A
B
C





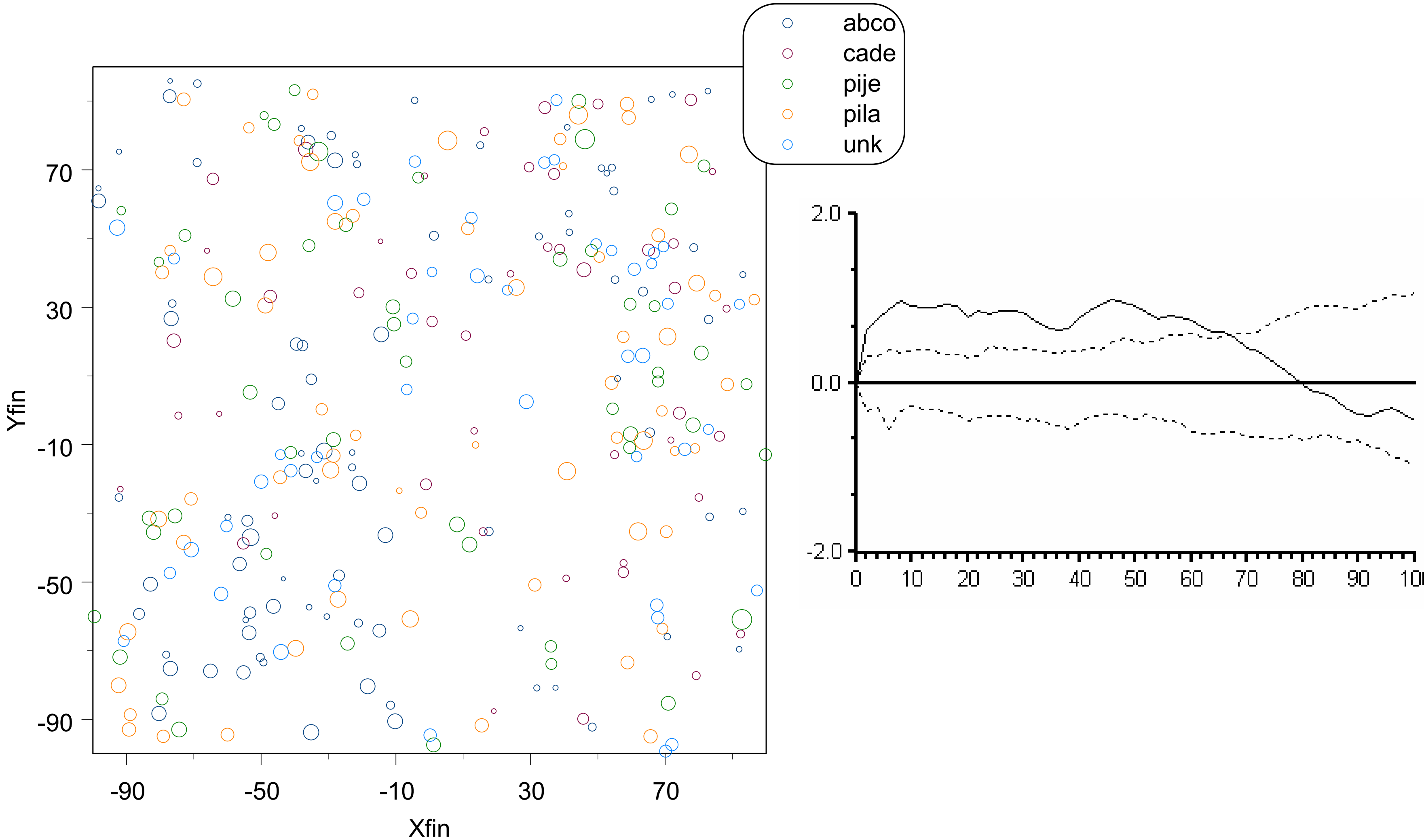


Thinning Level:	Unburned	Burn
None	Control (UN)	Burn Only (BN)
Understory thin (25 cm < thin <76 cm)	Unburned/Thin from below (UU)	Burn/Thin from below (BU)
Overstory thin (25 cm < thin & leave 22 large t/ha)	Unburned/Overstory thin (UO)	Burn/Overstory thin (BO)

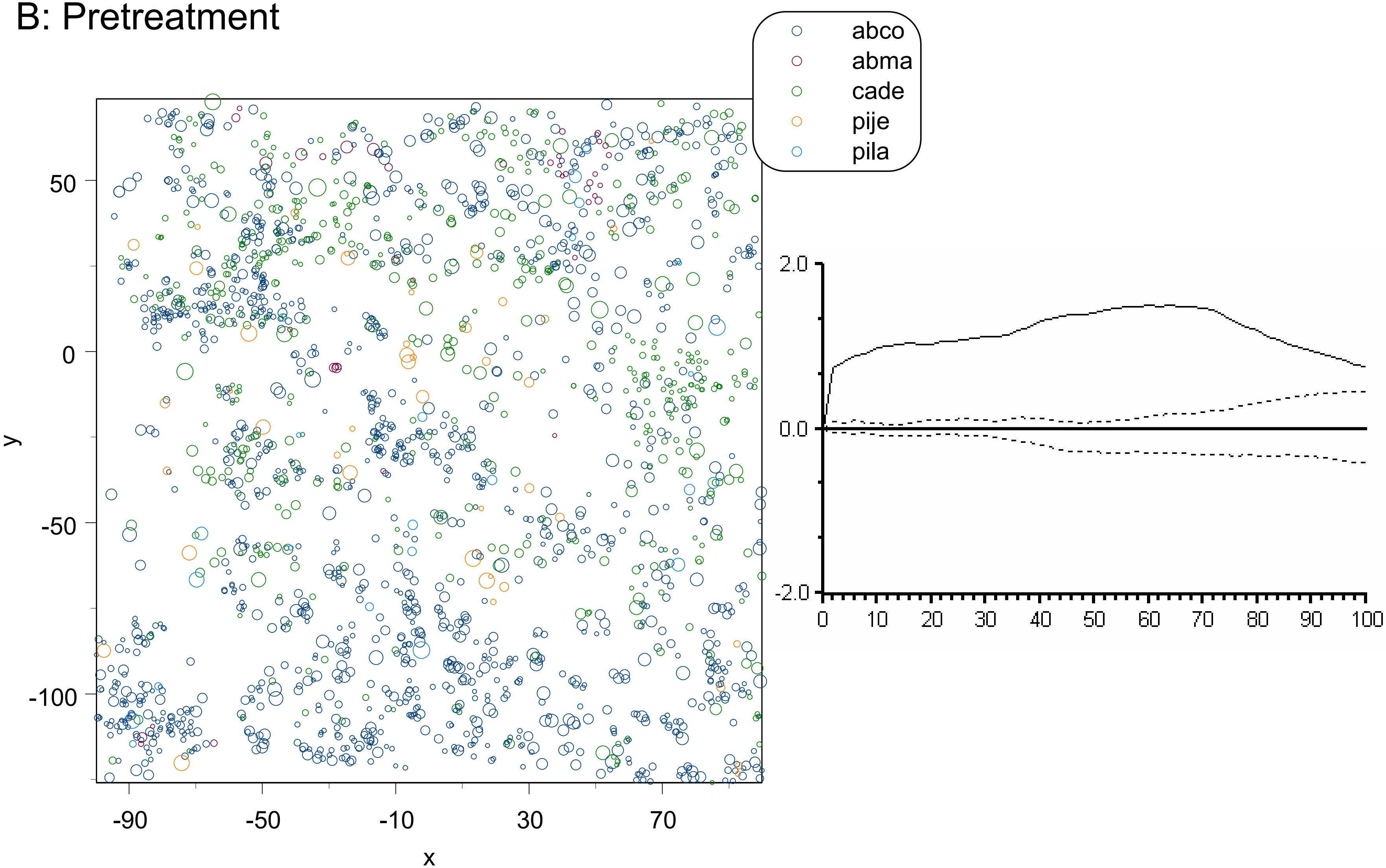


Pretreatment
Burn/No thin
Unburned/Understory thin
Burn/Understory thin
Unburned/Overstory thin
Burn/Overstory thin
1865 Reconstruction
Density (# of stems/ha)
245
205
165
125
85
40
30
20
10
0
0 5
25
50
75
100
125
>150
25 cm dbh size classes

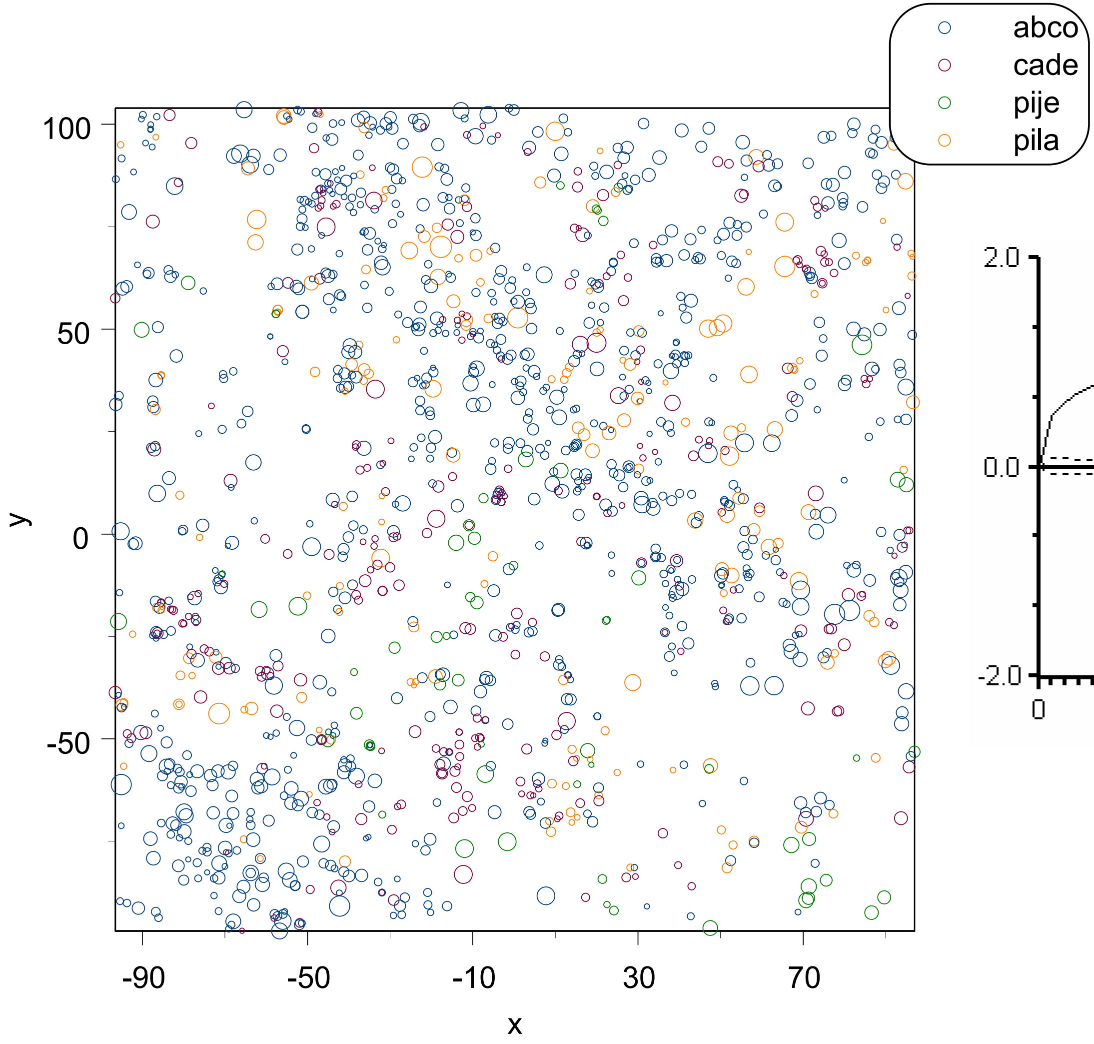
A: 1865 Reconstruction

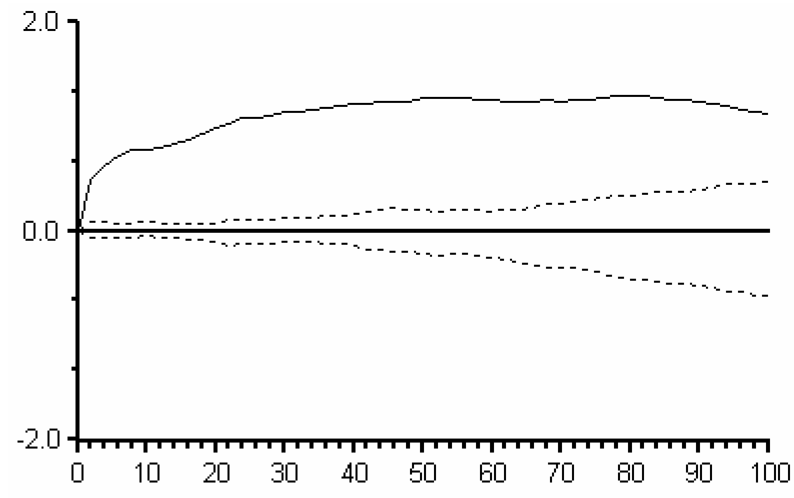


B: Pretreatment

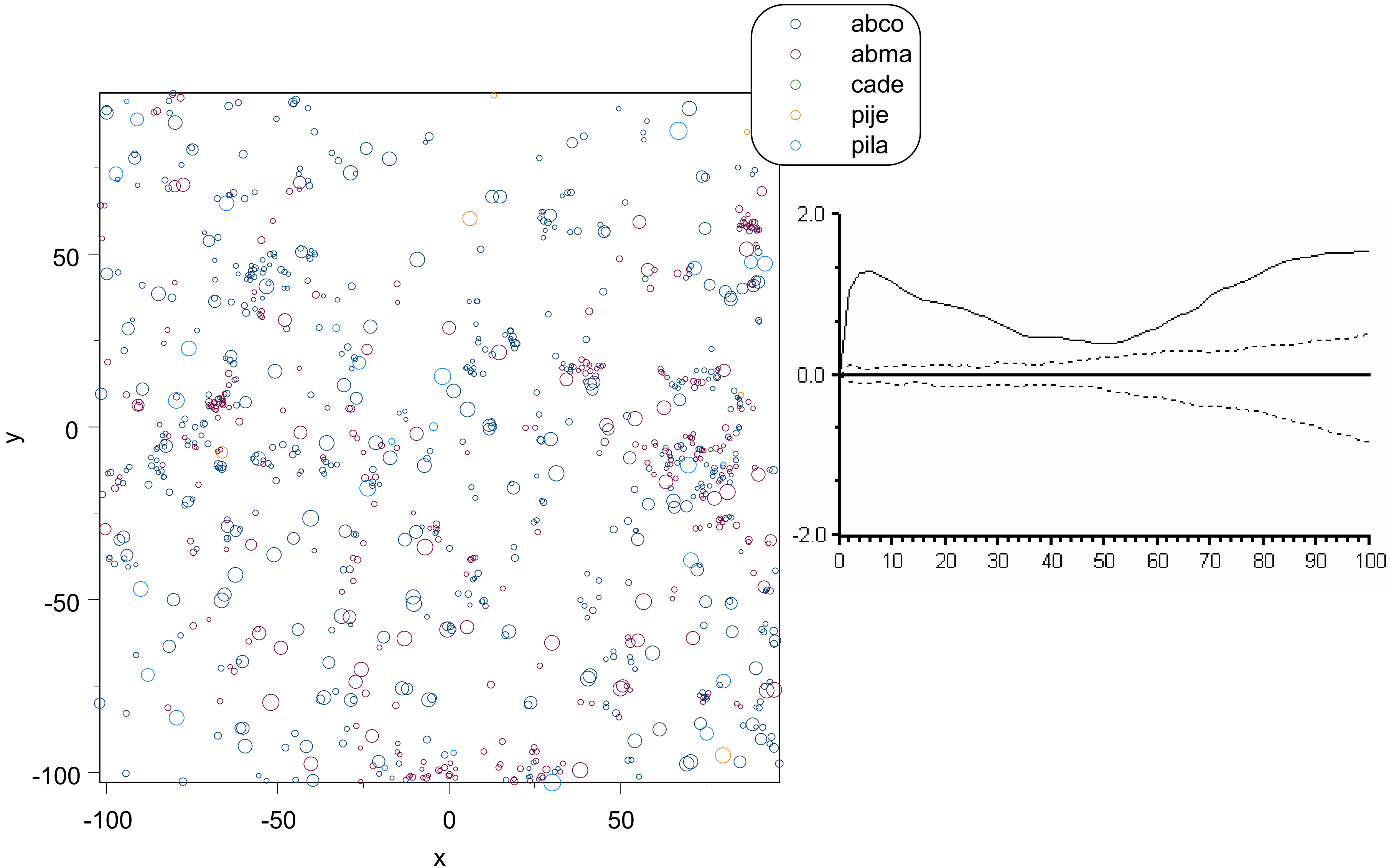


C: Burn/No Thin

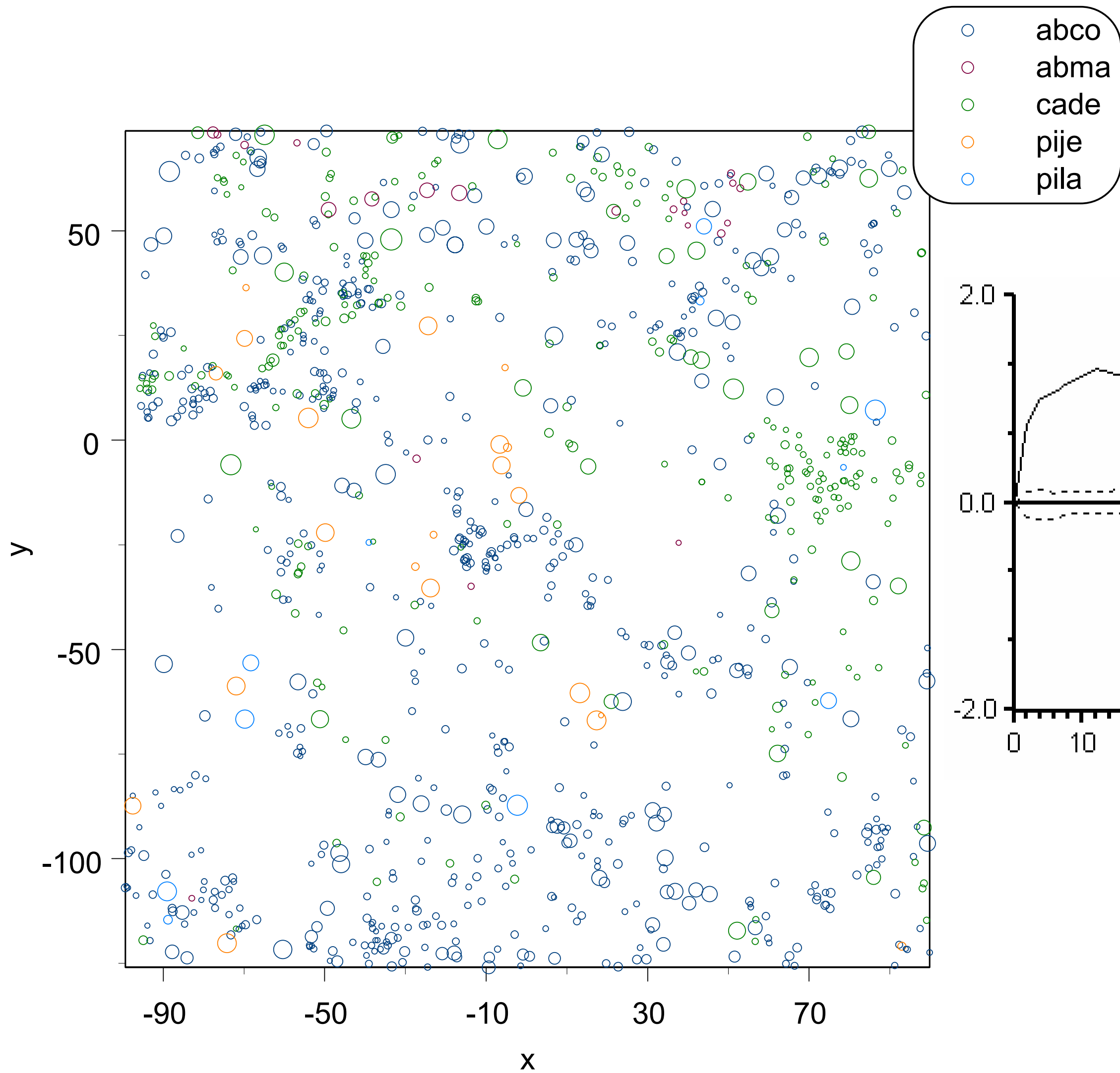


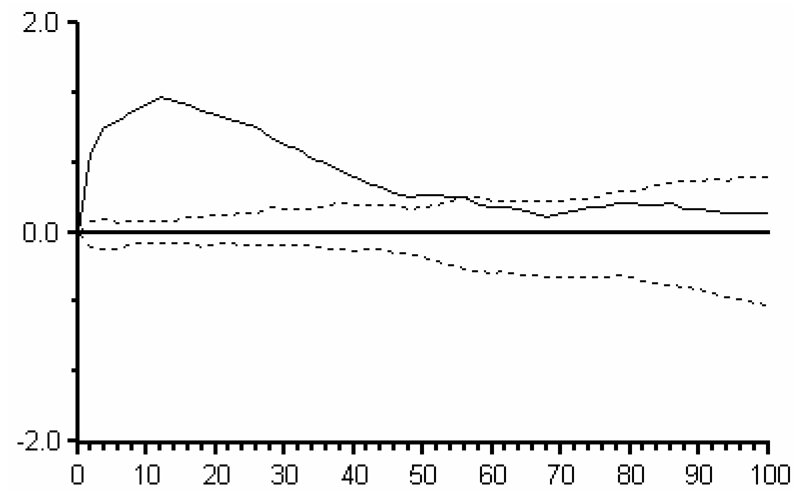


D: Unburned/Understory Thin

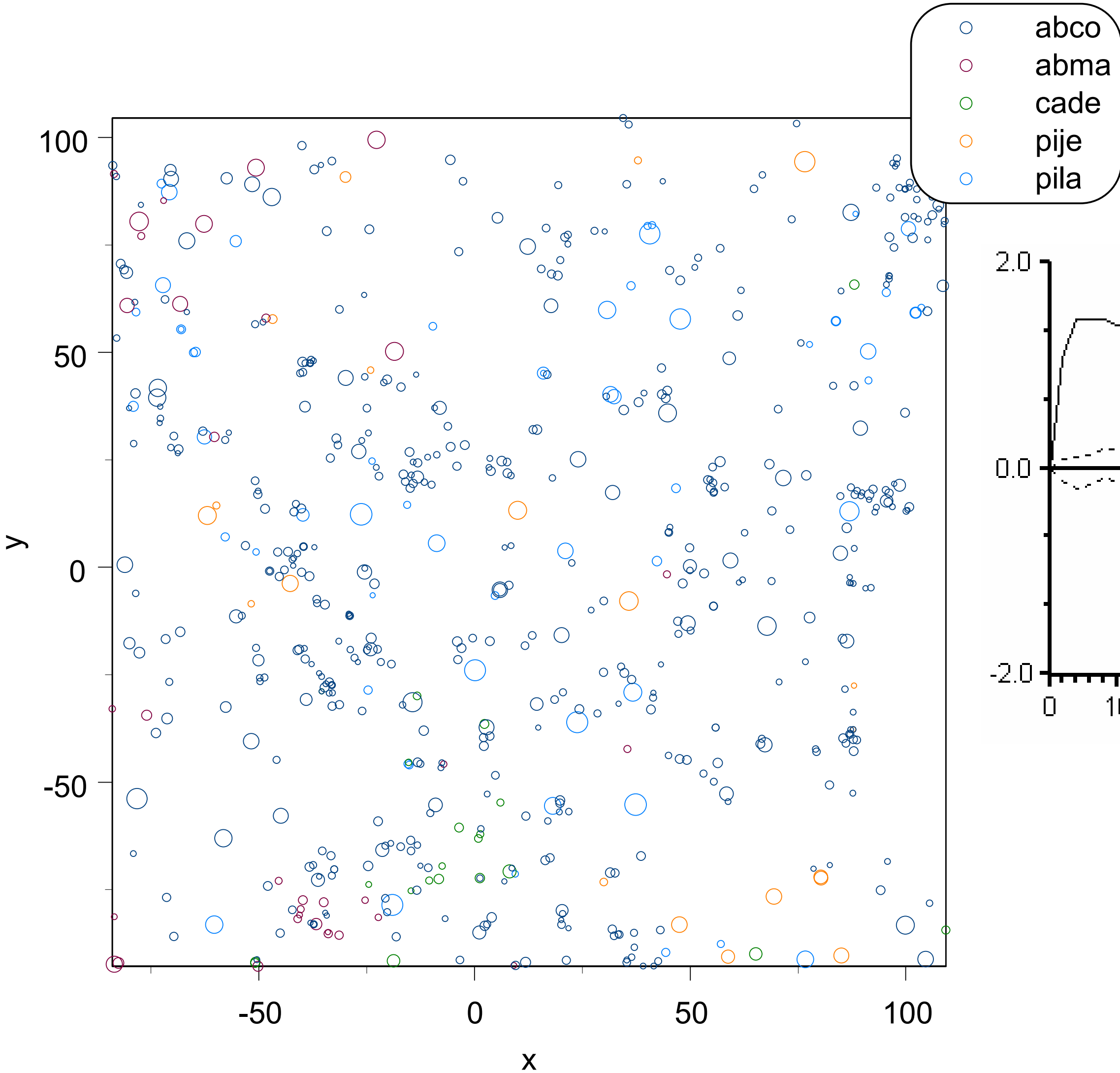


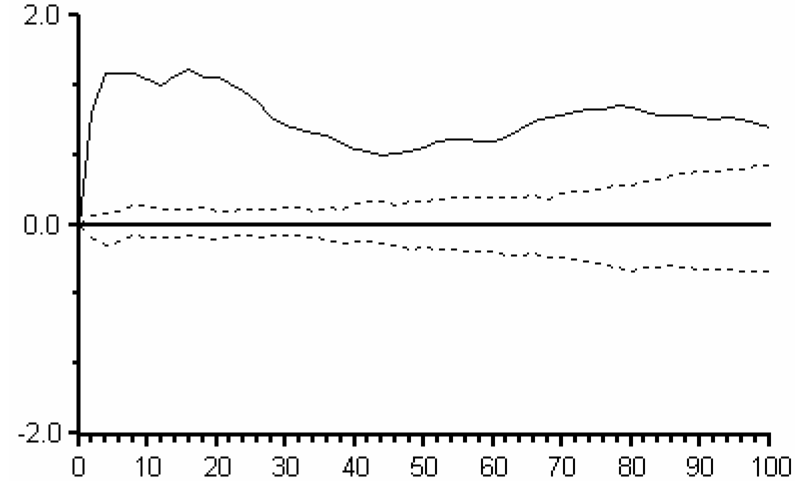
E: Burn/Understory Thin





F: Unburned/Overstory Thin





G: Burn/Overstory Thin